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Detection and response to critical lead vehicle deceleration events with peripheral vision: Glance response times are independent of visual eccentricity

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ABSTRACT

Studies show high correlations between drivers' off-road glance duration or pattern and the frequency of crashes. Understanding drivers' use of peripheral vision to detect and react to threats is essential to modelling driver behavior and, eventually, preventing crashes caused by visual distraction. A between-group experiment with 83 participants was conducted in a high-fidelity driving simulator. Each driver in the experiment was exposed to an unexpected, critical, lead vehicle deceleration, when performing a self-paced, visual-manual, tracking task at different horizontal visual eccentricity angles (12°, 40° and 60°). The effect of visual eccentricity on threat detection, glance and brake response times was analyzed. Contrary to expectations, the driver glance response time was found to be independent of the eccentricity angle of the secondary task. However, the brake response time increased with increasing task eccentricity, when measured from the driver's gaze redirection to the forward roadway. High secondary task eccentricity was also associated with a low threat detection rate and drivers were predisposed to perform frequent on-road check glances while executing the task. These observations indicate that drivers use peripheral vision to collect evidence for braking during off-road glances. The insights will be used in extensions of existing driver models for virtual testing of critical longitudinal situations, to improve the representativeness of the simulation results.

1. Introduction

Driving is a complex task that requires the driver to be vigilant and visually attentive to both the road in-front and the surroundings to stay safe. Although off-road glances by checking rear-view mirrors and blind spots are an inherent part of driving, in particular longer glances away from the road in front has been related to a higher crash risk (Horrey and Wickens, 2007; Klauer et al., 2014; Victor et al., 2014). With an increasing number of in-vehicle displays and nomadic devices, such as smart phones, drivers become similarly more and more prone to direct their gaze away from the road in front. Consequently, it is necessary to understand how the glance behavior influences the driver's reaction to upcoming threats, and, ultimately, the overall impact on traffic safety.

Numerous studies (e.g., see Dukic et al., 2005; Lamble et al., 1999; Larsson et al., 2017; Olaverri-Monreal et al., 2013; Wittmann et al., 2006), have been conducted on the placement of in-vehicle information displays and/or controls, and how to optimize the interaction with the driver. It has been observed that the mean duration of off-road glances to a secondary task may not necessarily increase with increasing eccentricity of the display or control (Dukic et al., 2005; Zhang et al., 2006). Also, the total off-road glance time may increase with eccentricity, since the glance frequency increases when the glance duration decreases (Fuller and Tsimhoni, 2009; Zhang et al., 2006). High eccentricity glances have previously been related to lead to longer brake reaction times to the approach of preceding vehicles (Lamble et al., 1999; Summala et al., 1996). The effect seems to be most prominent for vertical angle eccentricity rather than horizontal eccentricity (Dukic et al., 2005; Lamble et al., 1999).

Collected evidence from research have led to regulations from authorities around the world to limit the detrimental effects of off-road glances. Japan Automobile Manufacturers Association, Inc. (JAMA) has published safety guidelines for in-vehicle information systems, including a recommendation to limit the downward viewing angle of information displays to a maximum of 30° (Japan Automobile

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Manufacturers Association Inc., 2004). Similar recommendations have been adopted by the European Statement Of Principles (ESOP) (The Commision of European Communities, 2008), the Alliance of Automobile Manufacturers (AAM) (Driver Focus-Telematics Working Group, 2006) and by the National Highway Traffic Safety Administration (NHTSA) (National Highway Traffic Safety Administration, 2013), all limiting the down vision to approximately 30°. The basis for this recommendation is research demonstrating that drivers who look at a display positioned within 30° of the forward roadway are still able to perceive the approach of a preceding vehicle in time to avoid collision (Yoshitsugu et al., 2000). Note, however, that even if displays placed at less than 30° eccentricity have been shown to produce more timely reactions than when placed at larger eccentricities, studies have shown that off-road glances are associated with delayed braking behavior and an increased crash risk also for smaller eccentricity angles (Dingus et al., 2006; Lee et al., 2018; Wolfe et al., 2019).

1.1. *Peripheral vision in driving*

Drivers tend to time the initiation of tasks that include off-road glances and are self-paced (i.e., the driver can initiate the task when s/he wants, such as navigation destination entry, interaction with phones, and even radio tuning) to situations of low complexity where the probability of unexpected events is low (Tivesten and Dozza, 2014). While looking off-road, drivers use their peripheral vision to operate the vehicle (i.e., keeping the vehicle in lane and detecting forward threats). For example, Summala et al. (1996) studied how lane keeping performance is influenced when the driver has their gaze directed towards a secondary task. The study concluded that the performance decreases with increasing visual eccentricity of the secondary task, and that, with experience, the driver can learn to keep lane position using peripheral vision. Also when having the gaze directed on-road, the peripheral view of the road edges and optical flow are used to guide steering and estimate the vehicle's lane position (Land and Horwood, 1995; Robertshaw and Wilkie, 2008). For longitudinal control, similar studies to the one by Summala et al. (1996) have been performed by Summala, Lamble, & Laakso (1998), and also Lamble et al. (1999), on the reaction to a lead vehicle slowing down while the driver is looking away. The authors used a forced peripheral paradigm where the drivers constantly had their gaze directed toward secondary tasks positioned at nine different locations and were instructed to brake as soon as detecting deceleration of the car ahead. It was concluded that the driver brake reaction time increases with increasing eccentricity level of the secondary task (Lamble et al., 1999). Several other studies have reported a relationship between gaze eccentricity and long reaction times. For example, Faerber and Ripper (1991) observed an increasing response time for detection of a visual stimulus as the eccentricity increased in a range of $0^\circ - 30^\circ$. Moreover, Burns, Andersson, and Ekfjorden (2000) reported that eccentricity, in particular in the vertical direction, had a major influence on motor response time for car drivers responding to a visual stimulus by pressing the brake pedal. The studied eccentricity angles ranged from 0° to 40° in the horizontal direction and from 9° to 51° in the vertical direction.

Studies show high correlation between off-road glance pattern and crash frequency (Dingus et al., 2006; Horrey and Wickens, 2007; Wierwille and Tijerina, 1998), which is not surprising since the predominant information used for driving is obtained by the vision system (Evans, 1991; Sivak, 1996). The vision system can be divided into peripheral and foveal vision, with the foveal vision corresponding to the area close to the center of the retina, having a high concentration of color sensitive cone photoreceptor cells which contribute to a high vision resolution (Carrasco, 2011; Land, 2006). In contrast, the peripheral vision corresponds to the more eccentric areas of the retina, dominated by the extremely sensitive rod photoreceptor cells which function in low light levels, but on the expense of resolution (Lee et al., 2017; Purves et al., 2001). The peripheral vision system plays an important role in driving since it, for example, helps the driver to detect important and unexpected events coming up in front of the vehicle, while the driver's foveal vision is directed somewhere else (e.g., when tuning the radio). Since the peripheral vision system is different from the foveal vision, making it harder to distinguish details (Anstis, 1974), and more prone to detect motion (McKee and Nakayama, 1984), the visual information reaching the driver's brain is not as detailed as had it been provided by the foveal vision. Hence, information coming from visual cues, may be degraded when accessed only by peripheral vision.

Several methods for studying eye-movement and event detection have been proposed in literature, such as object and event detection methods (OED) assessing the reaction to objects and events commonly encountered while driving (e.g., see the summary by Victor et al., 2008) and signal detection tasks such as the peripheral detection task (PDT) (Martens and van Winsum, 2000; van Winsum et al., 1999) where the drivers are subject to artificial stimuli not naturally encountered while driving. The PDT task was originally developed to study the apparent narrowing of the visual field due to cognitive load, called *visual tunneling*. Visual tunneling is an alleged reduction in visual sensitivity in the periphery due to higher cognitive load (i.e. that the effects of cognitive load are larger in peripheral than in central areas of the visual field). That is, the visual degradation is dependent on both cognitive load and eccentricity. However, studies have shown little support for the visual tunneling effect at the larger eccentricities relevant for driving (e.g., see Recarte and Nunes, 2003; van de Weijgert, 1993), although there may still be some attentional degradation effects from cognitive load (cognitive tunneling), due to general attention selection (van Winsum et al., 1999). Instead, the *general interference* hypothesis has been proposed, stating a general visual degradation across the entire visual field, where the effect from cognitive load is independent of eccentricity (van Winsum, 2018; van Winsum et al., 2000). This implies that influence of cognitive load during driving will be independent from where in the visual field the stimuli is presented, making it easier to separate effects of cognitive load from effects of visual eccentricity when studying driving data. Note that the visual degradation of *sensitivity* (general interference or visual tunnelling) is a separate effect from *gaze concentration* (e.g., from cognitive load or driving demands, see Victor et al., 2008, 2005). Whereas gaze concentration is an effect on eye movements (breadth of scanning), visual sensitivity reduction occurs across the visual field independent of eye movement.

The degradation of visual information due to eccentricity may, however, be different for different types of visual cues. It has been shown that most visual performance deteriorates with increasing eccentricity (e.g., see Land, 2006; Seiple et al., 2004, or the review by Strasburger et al., 2011), with the exception of the perception of motion. A central visual cue for the detection of a forward threat is looming, which describes the optical expansion of a closing object at the observer's retina. Studies of looming detection by the peripheral vision indicates that the perception of radial looming (i.e., optical expansion from a center point) is independent of retinal eccentricity (Li and Laurent, 2001; Stoffregen and Riccio, 1990). Stoffregen and Riccio (1990) performed a controlled experiment comparing the response to looming of an artificial disk expanding on displays positioned at the center of the visual field and at 90° eccentricity respectively. They concluded that the differences in responses for the two cases were significantly smaller than the similarities. Li and Laurent (2001) performed a similar study with real objects approaching at different eccentricities ranging from 0° to 80°, where the participant task was to dodge the object (a ball) when they judged appropriate to do so. All participants managed to successfully dodge the ball at all eccentricities, which supports Stoffregen & Riccios (1990) conclusion that radial looming is not influenced by eccentricity.

1.2. Drivers' response processes

The role of visual cues for the driver is twofold: The most apparent is perhaps the role to guide the driver's actions, but the equally important first step is to guide the driver's visual attention by directing their gaze. Visual attention can be seen as a selection mechanism which filters an enormous amount of information and finds what is relevant for the task at hand (e.g., see Carrasco, 2011; Corbetta and Shulman, 2002, or the historical review by Tsotsos et al., 2005). Thus, the automobile driver must, at least intermittently, scan the environment and use their attention to identify which information to act upon. Driving can be considered to be influenced by both top-down and bottom-up attention selection mechanisms (Summala and Räsänen, 2000; Theeuwes and Hagenzieker, 1993), with the saliency driven bottom-up attention directing the driver's gaze towards salient features in the visual field, such as the looming of a car in front. Nonetheless, the driver's response process is not only directed by the bottom-up attention, but may be influenced by other factors such as distraction, for example if the driver is currently performing a secondary task. According to the general interference hypothesis, task load (visual and cognitive component) may lead to longer reaction times, regardless of the eccentricity or modality at which the load is presented (van Winsum, 2018; van Winsum et al., 1999).

To model the driver's reaction to a detected threat, it is necessary to understand the entire response process of the driver. There is no standardized way of quantifying this process and most studies are limited to a specific part of the response process, for example, time to brake relative to some stimuli (Green, 2000). Morando, Victor, Bengler, and Dozza (2019), broke down the reaction chain into three distinct components: (1) the *visual component*, for example glance response time and glance direction, (2) the *motor component*, for example reaction time for moving hands or feet, and (3) the *intervention component*, for example timing and choice of an avoidance maneuver. By studying each component in the response chain, they could separate how different test conditions and test subject variability influenced the individual parts in the response process, both in terms of order, timing and duration.

Natural human response processes contain variability from various sources, including errors, and deviations from dominant or stereotypical performance. When modelling human response processes, it is necessary to separate dominant (more frequent) responses from responses resulting from errors or other performance deviations that may obscure effects that are the target of modelling. A first step can be to quantify the dominant behavior, and thereafter, as needed, include less common behaviors, so as to avoid oversimplification in modelling. For example, the stereotypical response process in a peripheral task may be looking at a peripheral display, then redirecting the gaze to the forward roadway due to detection of motion or looming, then reaction and intervention. However, human performance deviations may also be present (e.g., frequent check glances to the road, or aborting execution of a secondary task). These deviating behaviors could be seen as an error of execution (if viewed in relation to completing the secondary task), or as a desired behavior (if viewed from a traffic safety perspective). This influence of point-of-view on interpretation of actions as errors or not has led to more neutral terminologies such as human performance deviations (see

Fig. 1. Camera view of the driver. The driver has given his consent to the use of the picture in publications.

Hollnagel et al., 2001). Nonetheless, error classification systems (e.g., Reason, 1990, based on Rasmussen, 1983) can be useful in developing typologies of behaviors for modelling purposes.

1.3. Modelling the driver's response process

Understanding and modelling the driver's response process is essential when estimating the road safety benefit of the increasing number of advanced driver assistance systems that are being developed and introduced for new vehicles (e.g., see Page et al., 2015). During recent years, driver response models for various types of traffic situations have emerged, such as steering interventions and gaze and/or braking response to a forward threat with/without an active driver assistance system (e.g., see the review by Markkula et al., 2012). Most traditional response models rely on probability distributions and predefined intervention profiles (e.g., see the review by Green, 2000), whereas some more recent models focus on the driver's response to visual cues such as looming (Fajen, 2005; Markkula et al., 2016). In a paper by Svärd et al. (2017), a quantitative model for brake onset and control in a critical longitudinal (rear-end) scenario is described. This model was built on the assumption by Markkula et al. (2016), suggesting that the driver's brake initiation is based on noisy evidence accumulation of perceptual cues (mainly looming) over time. This means that the driver continuously collects perceptual input that are indicative for an upcoming need to slow down. When the total sum of the collected input exceeds a certain level, an avoidance brake maneuver is initiated. Furthermore, the authors describe the driver's braking response using neuroscientific concepts such as motor primitives (Giszter, 2015), and prediction of sensory outcomes of motor actions (Crapse and Sommer, 2008). Although the model produces kinematics-dependent brake initiation and brake ramp-up that reproduces the trends in naturalistic driving data, it has, similarly to most other driver braking models, a limitation in that it assumes that the driver does not accumulate any perceptual input during off-road glances.

The aim of this paper is to contribute to the computational modelling of drivers' response processes in a critical longitudinal (rear-end) traffic scenario, by quantifying how peripheral vision is used to accumulate perceptual evidence of deceleration of a lead vehicle. Specifically, we study drivers' responses to perceptual input during off-road glances of various degrees of eccentricity, in the critical rear-end scenario. Focus is

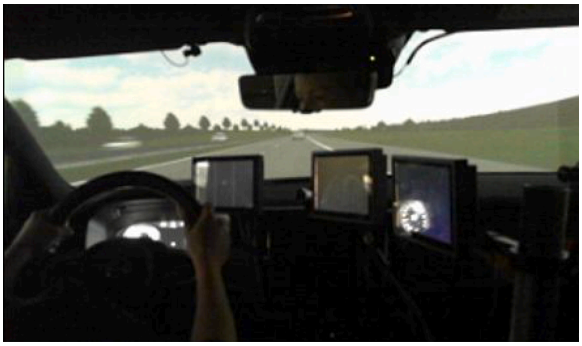

Fig. 2. Camera view of the secondary task, touch screen, monitors, steering wheel and forward roadway.

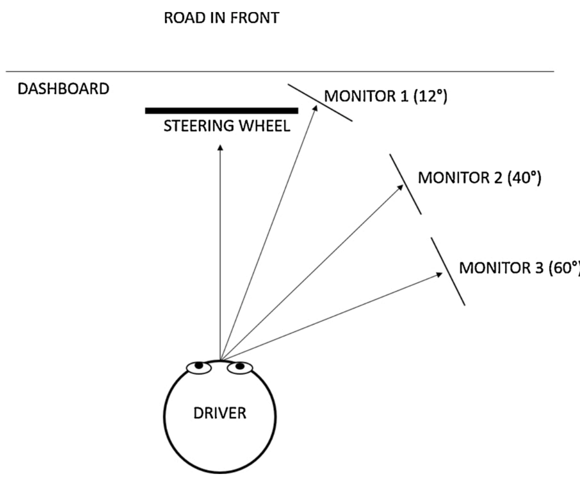

Fig. 3. Schematic view of the secondary task monitor positions, seen from above.

on both the visual and the intervention components in the response process, more specifically glance redirection time and brake initiation. Having identified relevant performance indicators guiding the driver's response process, these can be used to extend existing computational response process models to consider the effect of gaze eccentricity. In addition, the effect of gaze eccentricity on the driver's tendency of performance deviations will be explored.

2. Method

A study based on a between-groups design experiment in a high-fidelity, moving-base, driving simulator was performed. Eighty-three drivers, divided into three groups, were subject to an unexpected, severe braking of a lead vehicle, during the performance of a visual-manual secondary task positioned at a different eccentricity for each group.

2.1. Simulator and measurement equipment

The experiment was performed in Volvo Cars Vehicle Dynamics simulator, a high-fidelity moving base simulator – based on DiM150 from VI-Grade. It was equipped with a Volvo SPA S90 cockpit, a Volvo S90 vehicle model from VI-CarRealTime and had nine degrees of freedom. The projection was done in full HD on a 210° screen around the cockpit. Two web cameras recording videos with a frame rate of 15 frames per second were setup inside the vehicle cabin. One camera was positioned close to the dashboard, monitoring the driver face, and one camera was set up in the rear of the cabin, focusing on the road in front and also capturing parts of the steering wheel, dashboard and monitors in front of and next to the driver. See Figs. 1 and 2 for examples of the camera views. In addition, three touch screen monitors for displaying a secondary task were mounted on an approximate half circle to the front-right of the driver, with the monitor mid-point positioned at a horizontal eccentricity of 12°, 40° and 60° relative to a straight line from the driver's eyes towards the road in front, in level with the upper part of the dashboard. See Fig. 3 for a schematic overview of the monitor positions. The setup is also shown in the camera view presented in Fig. 2. To ensure that the viewing angle to the monitors were in the same range for all drivers, the driver seat was fixed in a position that should be comfortable enough for most drivers. Before starting to drive, the participants were asked to adjust the seating position to the least extent possible, while still judging it comfortable enough to drive for 45 min (most drivers did not adjust their seats and the absolute extreme values of the angles for individual drivers were 10°–12°, 33°–46° and 47°–67°, with a mean angle of 12°, 39° and 58°, respectively for the 12°, 40° and 60° groups). Vehicle signals and driver input were measured and stored using a DEWESoft S-Box data acquisition unit equipped with DEWESoft X2 data acquisition software.

2.2. Test participants

All test participants were randomly selected employees at Volvo Car Corporation, individually recruited through a participation request and a follow-up screening questionnaire for those that showed interest in participation. All selected participants had the option to not take part in the study and they could cancel their participation at any time, without stating why they chose to do so. The study was a between-group design with a total of 83 participants, divided into three groups. Each group was to perform a visual-manual secondary task at different eccentricities during an unexpected critical lead vehicle event. The main difference between the groups was at which eccentricity the task was presented during the critical event, which was at either 12°, 40° or 60°. The number of test participants in each group was: 23 (12° group), 24 (40° group) and 36 (60° group). The higher number of participants in the 60° group was motivated by an expected lower number of driver brake responses for high eccentricities. The participants were predominantly male, 77 %, and the age was distributed between 24 and 62 years with a mean age of 36 years. The participant selection criteria included a desire that they should have held a driver's license for more than five years and should preferably drive a yearly distance of more than 5000 km. To be able to keep the driver seat in approximately the same position for all drivers, and thus have approximately equal eccentricities to the secondary task monitors for all drivers, participants were not to be taller than 190 cm.

2.3. Secondary task

All drivers were instructed to perform their best at a game-like secondary task, activated at one of the monitors approximately every 1.5–2 min during the driving session. A sound in combination with one of the touch screens lighting up alerted the drivers each time they were expected to start the task. All drivers performed the secondary task at all monitors (i.e. at all eccentricities), but only at one monitor at a time. However, the critical event, occurring only once per driver, was designed to take place when the driver performed the secondary task at a specific eccentricity, which was different for each group in the study. The task consisted of a self-paced tracking game inspired by the surrogate reference task, SuRT (International Organization for Standardization, 2012), designed to make the drivers look off-road for 3 s during the critical event. When not exposed to a critical event, the required time that the driver had to look at the task to be sure to succeed was slightly shorter (0.5–2.5 seconds), and random.

The secondary task was designed as a 30 s long game sequence

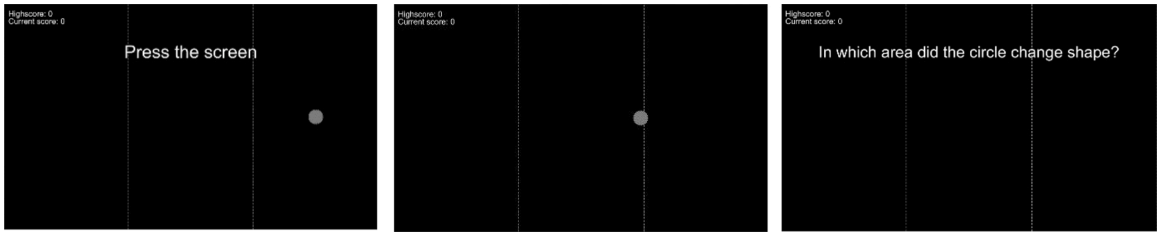

Fig. 4. Screenshots from the secondary task used in the experiment.

divided into several game rounds (usually 2–6 rounds, depending on the pace preferred by the driver), where the driver had the possibility to look back on-road and stabilize the vehicle between the game rounds. See Table A1 in Appendix A for a game sequence overview and corresponding actions expected from the driver. Each game round was initiated by the driver pressing the touch screen, making the total number of game rounds dependent on the preferred pace of the driver. A countdown from three to one followed the screen press and prepared the driver for the start of the subsequent game round. During the countdown, the driver could still perform on-road glances without risk of failing the current game round. After countdown, a grey disc started to move horizontally back and forth on the screen, at one point changing shape to a diamond for a small fraction of time, before changing back to disc shape again (it was approximately 100 ms from the start of the change to the diamond shape to when it was a disc again). When the disc disappeared, the driver's task was to, by pressing the touch screen, choose the one of the three regions in which the change of shape took place (the three areas being of equal size and divided by a thin dashed line). Fig. 4 shows the start screen of each round (left), the game board during a game round (middle) and the screen displaying the question that ended each game round (right). After giving an answer, the driver got feedback whether the given input was right or wrong. Eventually, when the 30 s game sequence was over, the total number of correct answers for that specific sequence was shown. The total driver score was recorded, but not presented to the driver during the test.

The disc speed, the moment of shape change and the game round duration was random at all times, except when the game was presented in relation to the critical brake event. The critical event was issued at the second game round in the corresponding game sequence and the disc changed shape in the last 100 ms of the event, which was three seconds long. Thus, the drivers were required to look off-road for the entire game round to not risk failing the task.

2.4. Simulated scenario

The driving took place on a simulated two lane, separated, highway with moderate traffic and the drivers were instructed to keep 90 km/h and to stay in the rightmost lane. There were random oncoming traffic, but all surrounding vehicles going in the same direction as the own vehicle were controlled to ensure that all drivers were exposed to the same driving conditions. A reverse adaptive cruise control algorithm was used to control the distance to other cars and ensure a correct time headway (THW) to the lead vehicle during the critical brake event. That is, the simulation environment modified the lead-vehicle speed to ensure the correct THW. Thoroughly piloting was necessary to make the traffic flow feel natural.

To ensure that the critical brake event was unexpected by the test participants, they were told that the objective of the experiment was to study lane keeping in relation to surrounding traffic. They were informed that to fulfil this objective, some vehicles may position themselves at a certain distance and follow the current speed of the test driver. The drivers were not informed that a critical event would occur during driving, but they were instructed to drive safely by not departing from the road and by not colliding with other road users. Furthermore, the drivers were given the instructions to perform their best at the secondary task game. None of the participants had previously participated in similar experiments in a simulator or on a test track.

To get used to the vehicle, the driving environment, and the secondary task each participant started with a 10−15 min long warm-up session where they got the opportunity to try playing the game. When the driver felt comfortable with the driving simulator and the secondary task, the real test session started. It was approximately 45 min long, but the critical event studied in this paper occurred after approximately six to eight minutes of driving. There was only one critical event per driving session, but at two occurrences before that event, the driver was presented to a close to identical traffic situation, but with the vehicle ahead accelerating away instead of braking.

For the critical event, a car positioned itself in the left lane at a THW of 2.4 s in front of the driver. During the first game round, the car changed to the rightmost lane. When the disc started moving in the second game round, a deceleration of 10 m/s^2 was initiated. The very high deceleration was necessary to complete the scenario, that is, to permit the lead vehicle to come close enough to the own vehicle for the drivers to respond, during the three seconds of off-road glance induced by the secondary task. Brake lights were inhibited during braking to not have several confounding factors in the analysis. To make the driver feel comfortable with the lead vehicle, there were two occurrences where the lead vehicle positioned itself in exactly the same way as during the critical brake event, but instead of braking accelerated away from the test driver. One of these occurrences happened during the warm-up session and one in the beginning of the actual test session.

2.5. Data preparation and dependent variables

The recorded data included information about the kinematics of the involved vehicles and the driver input in terms of, for example, brake pedal position and steering wheel angle. However, no eye tracking equipment was used but the driver glances were manually annotated. Moreover, the looming profile from the lead vehicle brake was calculated using the relative speed and distance to the lead vehicle in combination with knowledge about the lead vehicle width.

2.5.1. Glance and response scoring

Glance data from the participants were obtained by manual annotation of the video recorded from the web cameras mounted in the simulator. Only the relevant parts of the test drive were annotated, that is, starting just before the critical event and ending after the event. To make the annotation consistent, it was done by only two persons and the result was reviewed by yet another person. The annotation was divided into four categories:

- Glance dwell on-road
- Glance dwell off-road (on secondary task)
- Glance transition towards on-road
- Glance transition towards off-road

According to the definition of glance in ISO 15007 (International Organization for Standardization, 2015), a glance is defined as the

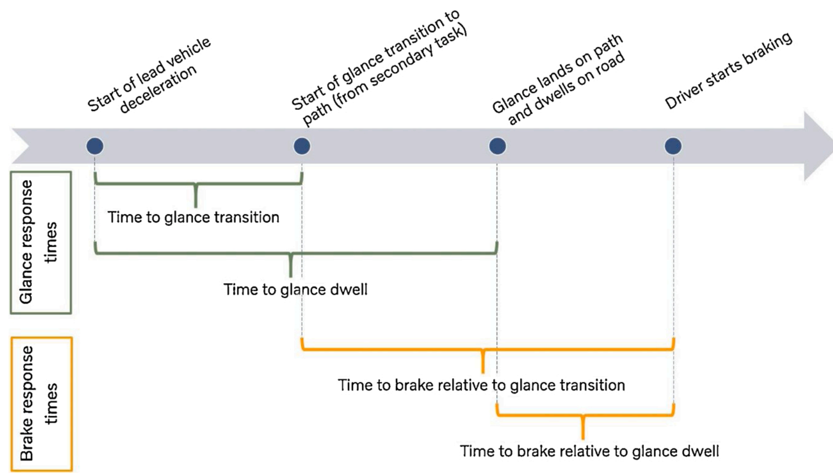

Fig. 5. Glance and brake response times in relation to the start of the critical event and the resulting driver reactions.

combination of several fixations on an area of interest (i.e., a dwell), also including the transition to and from the focus area. Here, a more detailed glance coding is performed (of dwells and transitions), which makes it possible to study the glance response process in more detail. Apart from glances, the start and end of the secondary task and the start of, potential, avoidance steering were also manually annotated based on the recorded videos. The start of the secondary task was defined as the first frame after end of countdown and task end was defined as the first frame displaying the final question of the game round.

2.5.2. Glance and brake response times

The glance response time of each driver was measured from the start of the deceleration of the lead vehicle, which occurred at, or just after, the start of the secondary task (the exact timing could differ a few milliseconds between the participants due to delays in the communication between the computer handling the secondary task and the computer handling the event). Two different measures were used: (1) Glance response time at glance transition start, defined as the time from start of lead vehicle deceleration to the annotated start of glance transition towards on-road, and (2) glance response time at glance dwell start, defined as the time from start of lead vehicle deceleration to the annotated start of glance dwell on-road.

Brake response time was measured in a similar way to obtain the brake initiation time relative to the two glance response times in the following measures: (1) Brake initiation time relative to glance transition, defined as the time between the annotated glance transition towards on-road and the first moment where the brake pedal signal exceeded zero (a value greater than zero signaled that the brake pedal was pressed by the driver), and (2) brake initiation time relative to glance dwell, defined as the time between the annotated glance dwell on-road and the first moment where the brake pedal signal exceeded zero. Since a glance starting at or after the end of the secondary task could be a induced by the end of the secondary task, such glances were disregarded when calculating both the glance and brake response times. Fig. 5 summarizes the glance and brake response times used for the analysis of the experimental data.

The statistical significance of between-group differences in response times was analyzed using both a frequentist approach, with a two sample two-tailed *t*-test (α at 0.05), and with a Bayesian approach (see Appendix B for details).

2.5.3. Human performance deviations

It can be hypothesized that proportions of drivers would not adopt the same dominant behavioral pattern during the event, causing the glance and brake response times to be excluded in parts of the analysis in this paper (e.g., an analysis of the dominant behavioral pattern). Such behaviors will in this paper be referred to as *human performance deviations*. The deviations can be divided into two main categories based on their consequences:

Human performance deviations resulting in data loss: Defined as human actions causing the event kinematics to change heavily or the glance pattern to have no off-road glances. These can be considered cases that should not be included in the driver response analysis and were divided into three categories:

- *Faulty event*: A mistake from the simulator operator caused the lead car to behave in an unintended manner (e.g. no lead vehicle brake).
- *High / low speed*: The driver did not follow the instructed speed +/- 18 km/h at event start. This would affect the severity of the lead vehicle brake in terms of the resulting looming profile.
- *No off-road glance*: The driver completely disregarded the secondary task and had the gaze directed on-road for the entire critical event. This resulted in very early avoidance maneuvers and no glance response time.

Human performance deviations resulting in several or very early on-road glances: Defined as performance deviations causing the glance pattern to be divided into several on/off-road glances or the driver to, presumably, redirect their eyes on-road because of factors other than the forward threat. These were divided into four categories, where the three first are different kinds of check glances:

- *Check glance*: A driver performing a complete on-road glance after a period of looking off-road, followed by a period of looking off-road again.
- *Short check glance*: A check glance where the on-road glance dwell part lasts for a maximum of two camera frames (corresponding to 0.13 s), followed by a period of looking off-road again for at least one second.
- *"What was that"-glance*: A check glance that is not followed by a period of looking off-road again. Instead, the driver has started the transition to direct the eyes off-road, but aborts the transition and redirects the gaze towards the road in front again before completing the off-road glance.
- *Too early glance back on-road*: A glance on-road due to, presumably, factors other than a forward threat. All on-road glances where the driver started the glance transition towards the road in front earlier than 1.9 s from event start were considered to be too early on-road glances.

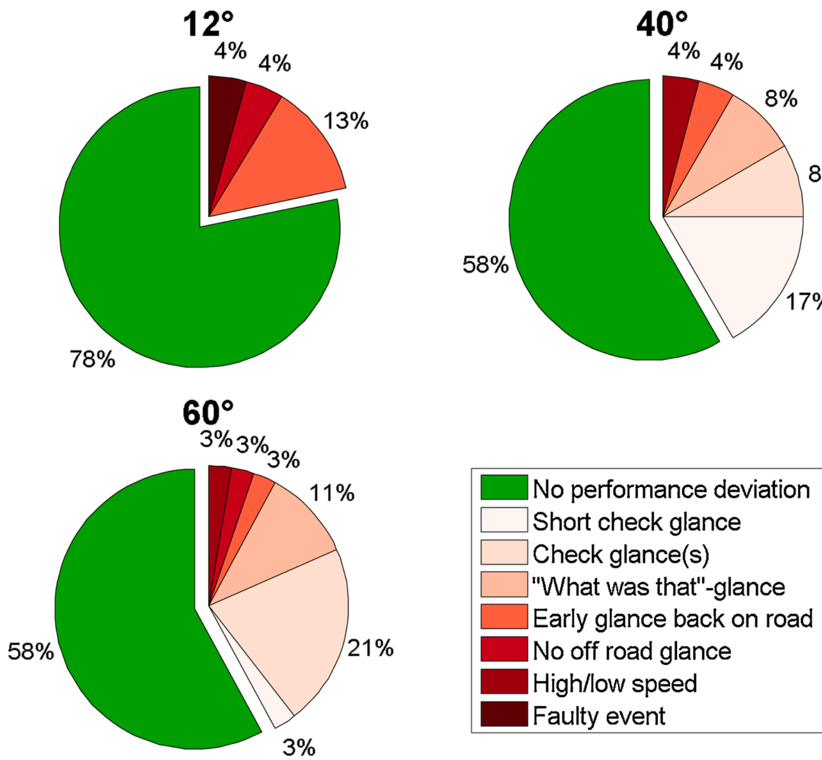

Fig. 6. The frequency of human performance deviations for each group of test participants.

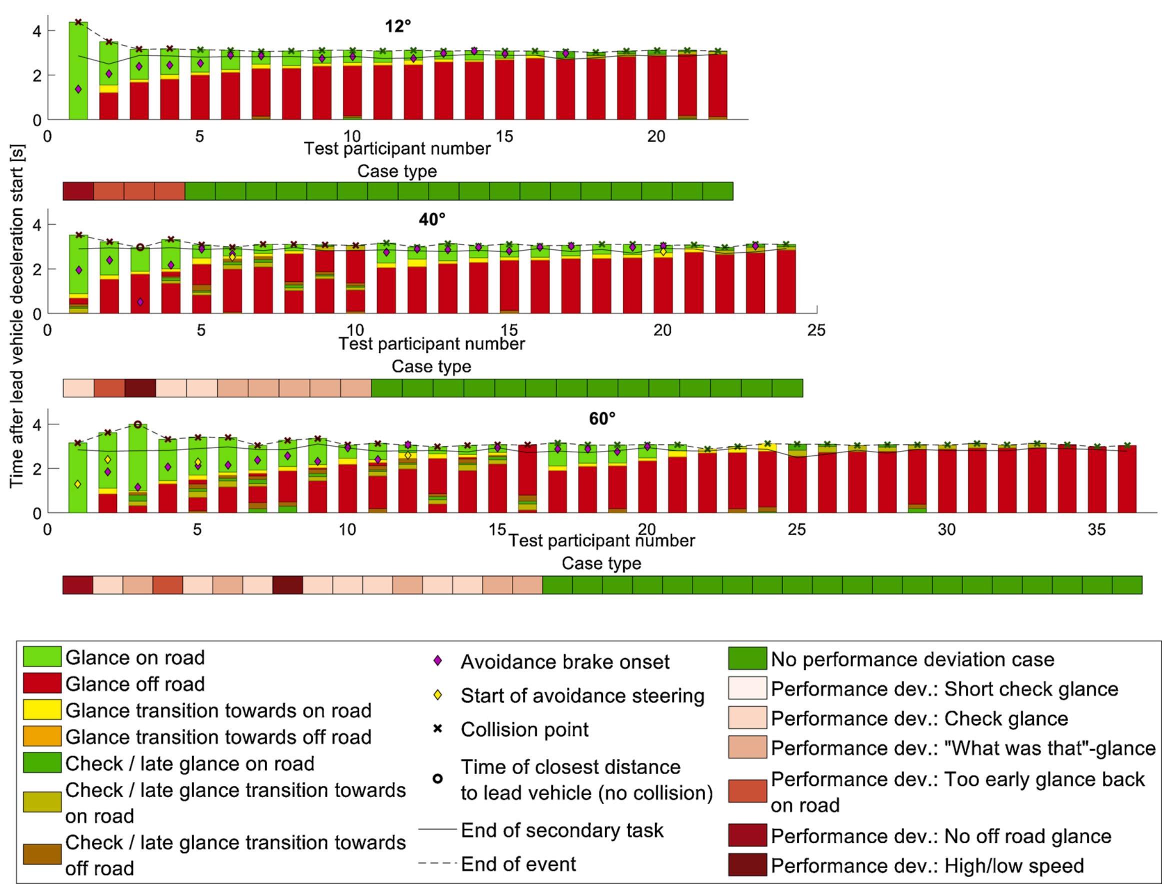

Fig. 7. Timeline for all test participants.

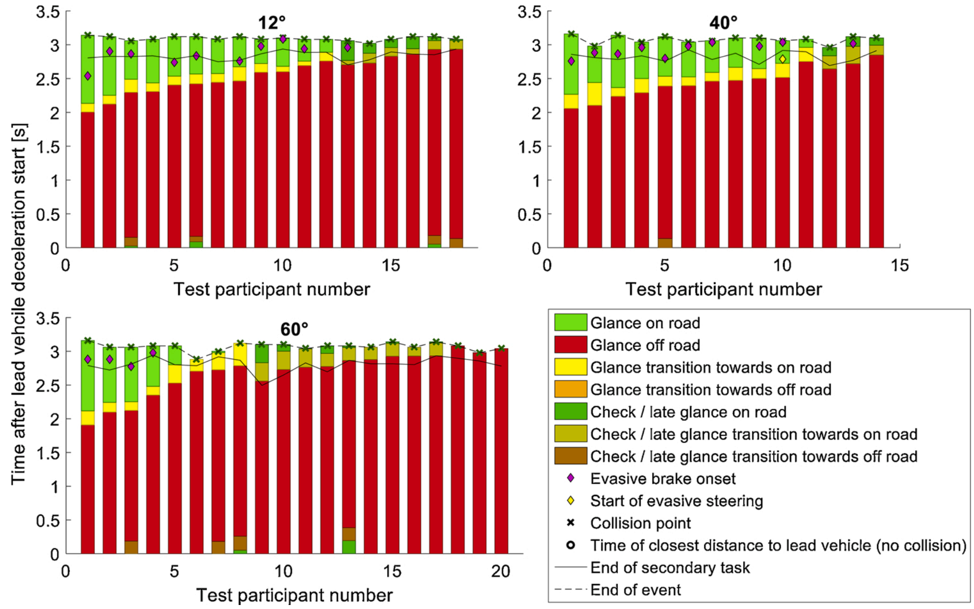

Fig. 8. Timeline for all test participants included in the detailed response process analysis.

To make a detailed analysis of the drivers' response processes in terms of glance and brake responses, it was required that the test participants were subject to as similar test conditions as possible. Therefore, all test participants corresponding to any of the performance deviations discussed above were excluded from this analysis. The human performance variability were however analyzed for all test groups to understand how the eccentricity influenced the frequency of certain performance deviations, in particular the influence on deviations resulting in several or very early on-road glances.

2.5.4. Looming profiles

The looming $\tau(t)^{-1}$ at time t, resulting from the lead vehicle deceleration, was calculated using the lead vehicle width w and the relative distance $x(t)$ according to Eqs. (1)–(3).

$$\theta(t) = 2\arctan\frac{w}{2x(t)} \tag{1}$$

$$\dot{\theta}(t) = -\frac{w\dot{x}(t)}{x(t)^2 + \frac{w^2}{4}} \tag{2}$$

$$\tau(t)^{-1} = \frac{\dot{\theta}(t)}{\theta(t)} \tag{3}$$

3. Results

The outcome from the simulator experiment was analyzed in two

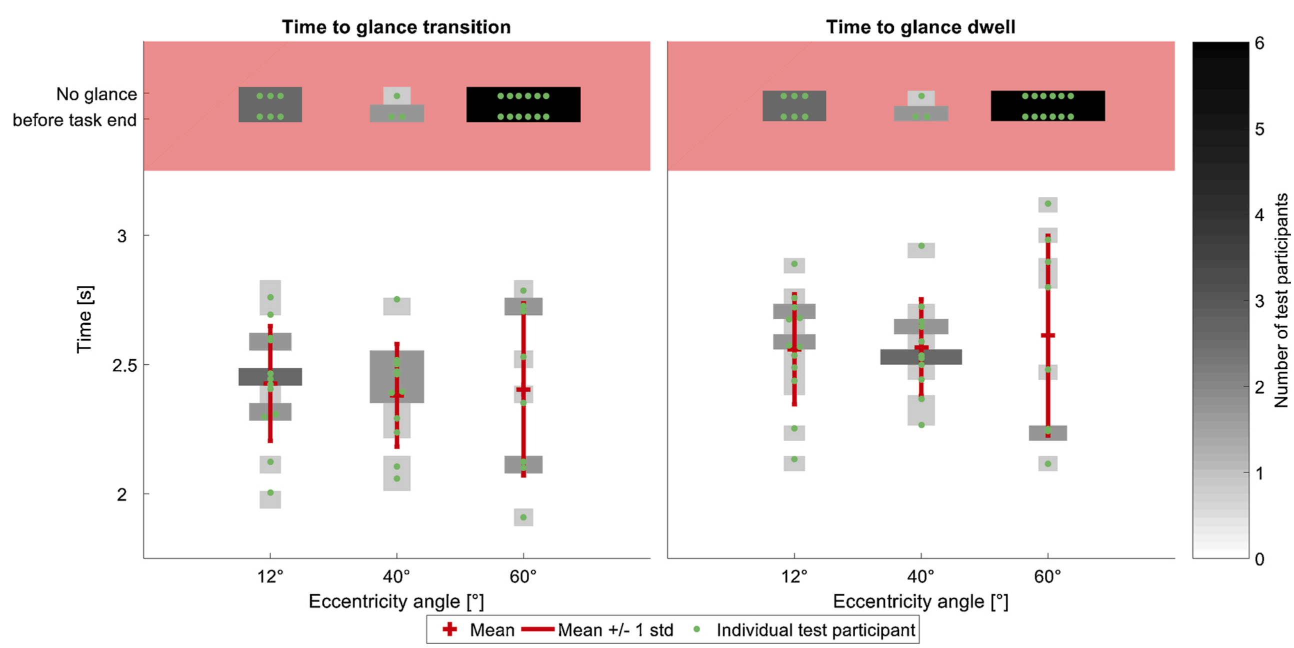

Fig. 9. Glance response times for all groups. The widths of the horizontal bars correspond to the number of test participants ending up in that bar, relative to the total number of test participants in the group, while the color of the horizontal bars reports the number of test participants in that bar, independent of group. The dots represent individual data points (i.e., the response times for individual drivers). *Left:* Time from lead vehicle deceleration start to start of glance transition. *Right:* Time from lead vehicle deceleration start to start of glance dwell.

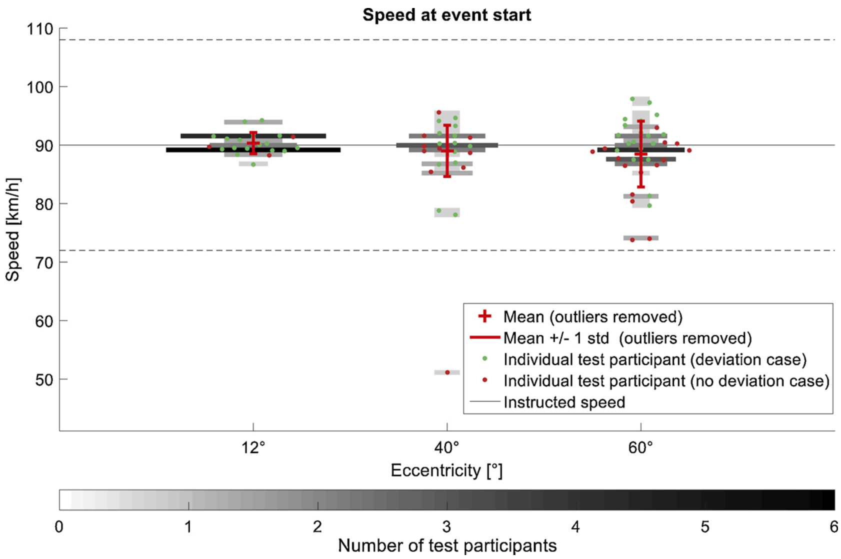

Fig. 10. Initial speed distributions for all groups and all test participants, measured at the start of lead vehicle deceleration. The mean and standard deviations are calculated excluding extreme outliers (> 3 standard deviations from mean). The widths of the horizontal bars correspond to the number of test participants ending up in that bar, relative to the total number of test participants in the group, while the color of the horizontal bars reports the number of test participants in that bar, independent of group. The dots represent individual data points (i.e., the response times for individual drivers).

steps: First, an overview of the responses from the complete set of test participants was performed and the frequency of common human performance deviations in relation to the given task was identified. In the next step, a subset of the participants, having responses relevant for the analysis of the response process in terms of glance and brake behavior, were selected for a more detailed analysis.

3.1. Overall driver responses and human performance deviations

The frequencies of human performance deviations for each eccentricity group, 12°, 40° and 60°, are shown in Fig. 6. It can be observed that the group corresponding to 12° eccentricity has a higher percentage of performances that were free from performance deviations (78 %) than the two groups corresponding to higher eccentricities (58 %). Noteworthy is that no check glances or "what was that"-glances occurred in this group, while that was the most common type of deviation for the higher eccentricity groups with 33 % (40° group) and 35 % (60° group) of the drivers performing some kind of check glance or "what was that"-glance. The 40° group had a higher amount of short check glances than the 60° group, while ordinary check glances where the most commonly observed human performance deviation in the latter.

For each of the 83 test participants, a time line of the brake event details was created, see Fig. 7. This provides an overview of all on and off-road glances and potential avoidance maneuvers during the event. In Fig. 7, it is also possible to see which of the test participants who had responses affected by one of the human performance deviations, these are depicted by with a red field below the main diagram. Since one of the aims of the experiment was to study the driver's response process in relation to a *forward threat*, all on-road glances that occurred later than, or maximally one camera frame (67 ms) before, the end of the secondary task's current game round, were specifically marked with a darker color in the timeline diagram, to be disregarded in the response process analysis. The reason for disregarding these glances was that the drivers were likely to look on-road again as soon as the game round was over, in order to stabilize the vehicle's speed and lane position before starting the next game round in the secondary task. In the same manner, check glances were treated separately and specifically marked with a darker color in the time line figure. In addition to glance pattern and avoidance maneuvers, Fig. 7 shows whether a collision occurred or not during the event. Due to the unexpected severe braking of the lead vehicle, the majority of the drivers were unable to avoid the collision.

3.2. Drivers' response processes

To make a detailed analysis of the drivers' response processes in terms of glance redirection time and brake initiation, all data points (i.e., test participants) corresponding to any of the human performance deviations discussed in Section 2.5.3 were excluded (see Appendix D for a data inclusion sensitivity analysis). This resulted in a total of 52 test participants remaining: 18 belonging to the 12° group, 14 belonging to the 40° group and 20 belonging to the 60° group. Fig. 8 shows the brake event timelines for all test participants included in the analysis.

In summary, it can be observed that both glance and brake responses occurred relatively late over all groups, resulting in a lead vehicle collision for all of the participants. The initiated on-road glances seem to be equally distributed in time for all groups, but with noticeably fewer drivers looking back before the end of the secondary task for the 60° group. To facilitate the analysis, the driver response process was broken down into two parts: glance response and brake response, each part analyzed separately.

3.2.1. The glance response process

When detecting a possible forward threat in the periphery while performing a secondary task, the first thing that the driver will do is to redirect their gaze by making a glance transition to fixate the road or object in front. The gaze redirection can be divided into a glance transition phase and a glance dwell phase, where the transition phase is defined as the movement of the gaze towards the road and the dwell phase is defined as the driver having the gaze completely back on-road. Fig. 9 shows the distribution of, as well as the individual test participants', glance response times, from the start of the lead vehicle deceleration to the start of the glance transition phase (left) and to the start of the glance dwell phase (right). All drivers who did not initiate a glance transition before task end are also visible in the upper (red) part of the diagrams.

There are two main observations that can be made from Fig. 9. The first is that several test participants did not manage to start their glance transition phase before the end of the secondary task. For the 60° group, the majority of the test participants (60 %) failed to start the glance transition in time. For the other two groups, the corresponding number

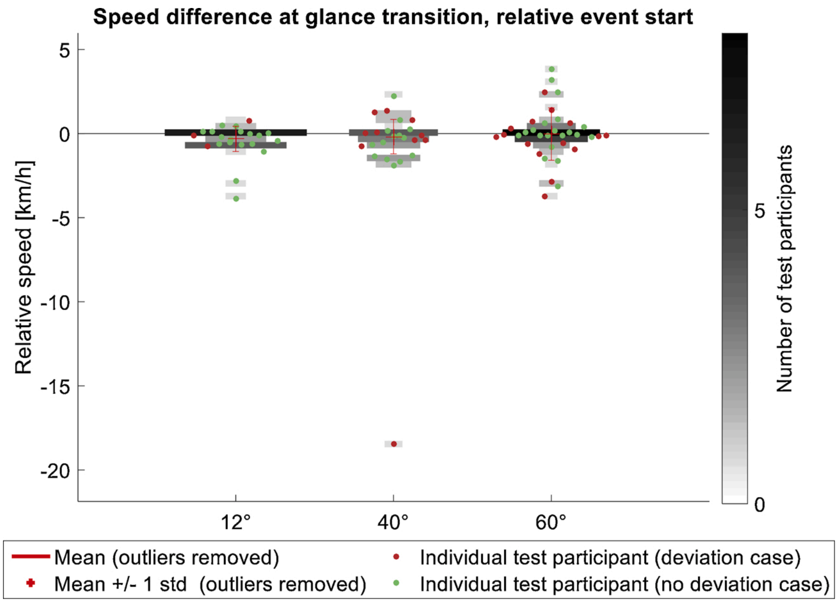

Fig. 11. Speed change relative initial speed, distributions at glance response for all groups and all test participants. *Left:* Speed change at start of glance transition. *Right:* Speed change at start of glance dwell. The mean and standard deviations are calculated excluding extreme outliers (> 3 standard deviations from mean). The widths of the horizontal bars correspond to the number of test participants ending up in that bar, relative to the total number of test participants in the group, while the color of the horizontal bars reports the number of test participants in that bar, independent of group. The dots represent individual data points (i.e., the response times for individual drivers).

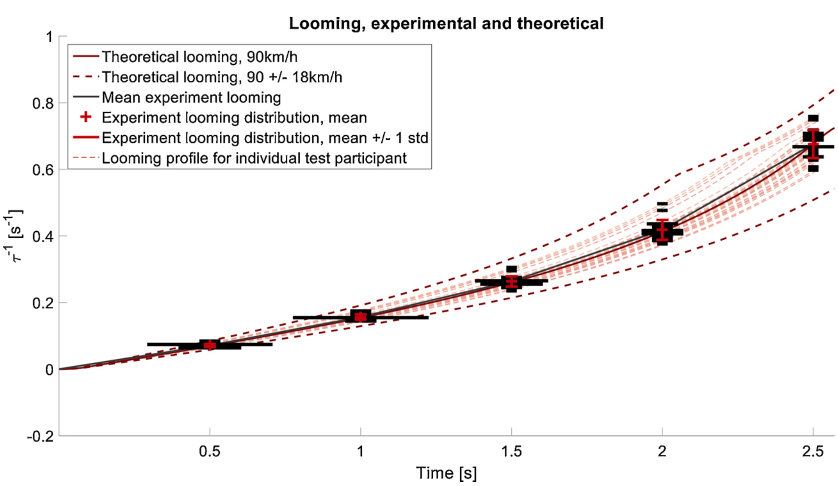

Fig. 12. Distributions of looming (black histograms) at different times for drivers with no human performance deviation, overlaid on actual theoretical (dark red lines) and experimental looming profiles (light red, dashed, lines). The time ranges from start of lead vehicle deceleration ($t = 0$ s) to the earliest brake initiation time among the drivers, since the subsequent braking will alter the looming profile. The widths of the horizontal black bars correspond to the number of test participants ending up in that bar, relative to the total number of test participants in the group. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

was 33 % (12° group) and 21 % (40° group). This is in accordance to what was observed in Section 3.1, where the analysis included the human performance deviation cases, the proportion of test participants looking back is much lower for the group of drivers looking away with a high eccentricity (60°), when compared to lower eccentricities (12° and 40°).

The second observation is that the glance response time, for the drivers that do look back before the end of the task, is similar across all eccentricity groups. This is true for both the glance transition start (with a mean, per group, of 2.43 s / 2.40 s / 2.40 s and standard deviations 0.22 s / 0.20 s / 0.34 s) and the glance dwell start (with a mean, per group, of 2.56 s / 2.57 s / 2.61 s and standard deviations 0.21 s / 0.19 s / 0.39 s). There is no clear difference between the groups, except for a small tendency towards a larger variance in response time for the 60° group, in particular for the start of glance dwell. In that group, a few test participants looked on-road relatively early and a few very late.

3.2.2. *Speed and looming variability*

A human performance deviation in terms of non-compliance to instructions (which can be categorized as a non-compliance routine error in Reason's, 1990, classification framework) that could largely influence the results of the current study is the speed of the subject vehicle during the lead vehicle brake event. The choice to accept the relatively large speed deviation of +/- 18 km/h, from the instructed speed of 90 km/h at the start of the brake event, was motivated to be able to include most of the test participants in the analysis, but still avoiding a too large spread in the final set of looming profiles. Fig. 6 shows that this speed interval disqualifies only 4% of the drivers from the 40° group and 3% of the drivers in the 60° group. The distributions of initial speeds are shown in Fig. 10. It can be observed that, in most cases, the initial speed is very close to the instructed speed, but the variance is slightly increased with increased eccentricity. The average speed is also somewhat lower for high eccentricities. A similar trend can be spotted in Fig. 11, illustrating the change in speed between lead vehicle deceleration start and the speed at glance transition start.

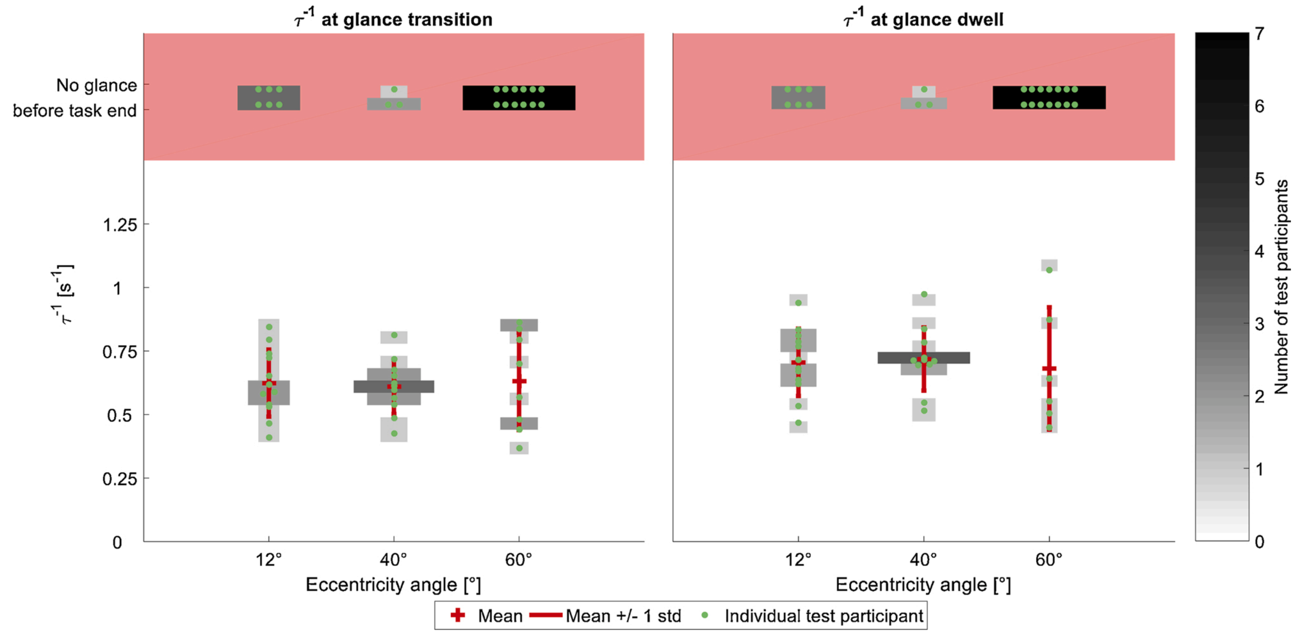

Fig. 13. Looming levels (τ^{-1}) at glance response for all groups, including only drivers with no human performance deviation. The widths of the horizontal bars correspond to the number of test participants ending up in that bar, relative to the total number of test participants in the group, while the color of the horizontal bars reports the number of test participants in that bar, independent of group. The dots represent individual data points (i.e., the response times for individual drivers). *Left:* Looming levels at start of glance transition. *Right:* Looming levels at start of glance dwell.

Recent publications have suggested that drivers mainly use looming to time their brake initiation (Fajen, 2005; Markkula et al., 2016; Svärd et al., 2017) and too different looming profiles might compromise the experimental results. However, Fig. 12 compares the theoretical differences in looming at different times during the brake event, where zero seconds corresponds to the start of lead vehicle deceleration (dark red lines). The actual looming profiles, calculated from relative speed and position, for each of the test participants are also plotted (light red, dashed, lines). It can be observed that even though the theoretical looming variability towards the end of the event is relatively large, the actual variability from the test participants is quite small. In Fig. 13, the distribution of looming levels at start of glance transition (left) and at start of glance dwell (right) are shown for each eccentricity group. It can be observed that the looming level at looking back is quite dispersed, but that the mean level seems independent of eccentricity. This is in line with the observation that the glance response times were also constant

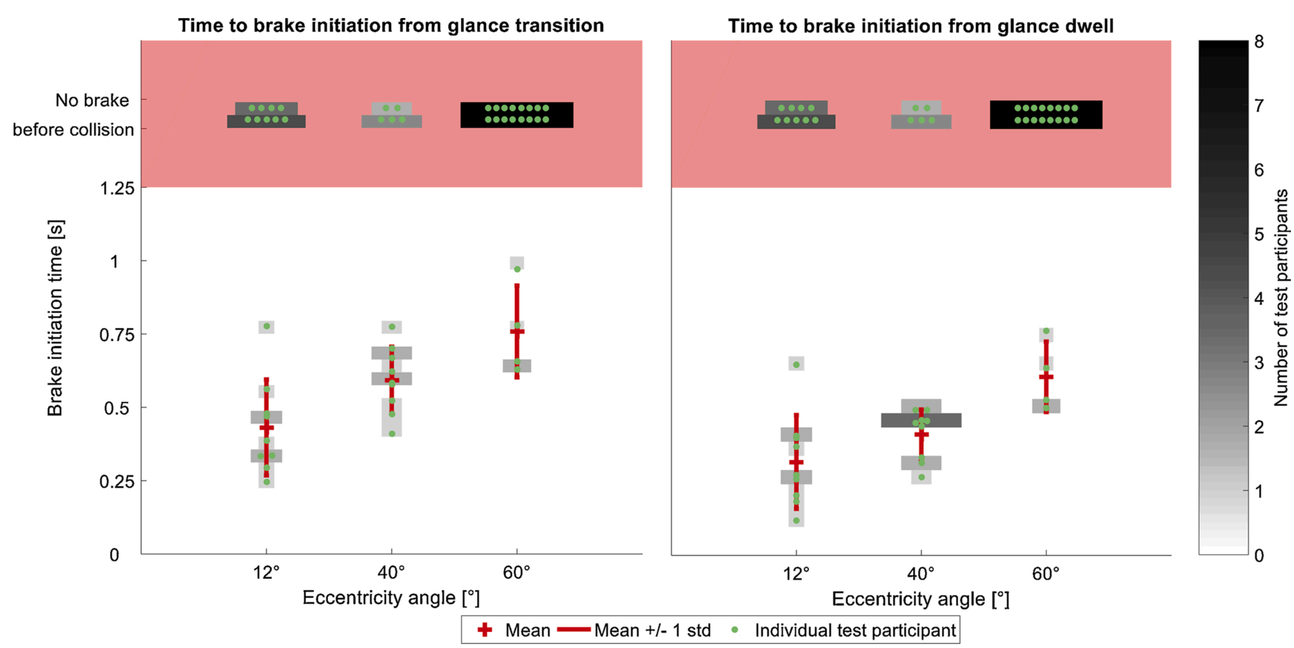

Fig. 14. Brake response times for all groups. The widths of the horizontal bars correspond to the number of test participants ending up in that bar, relative to the total number of test participants in the group, while the color of the horizontal bars reports the number of test participants in that bar, independent of group. The dots represent individual data points (i.e., the response times for individual drivers). *Left:* Time from start of glance transition to brake initiation. *Right:* Time from start of glance dwell to brake initiation.

Table 1
Results from statistical significance tests and effect sizes for increasing brake initiation times with increasing eccentricity.

Test	*t*-test (p-value)	ROPE (95 % HPD)	Cohen's d
Brake initiation time relative to glance transition			
12° group / 40° group	Sign. (p = .0433)	Marginally sign.*	.39
12° group / 60° group	Sign. (p = .0081)	Sign.	1.3
40° group / 60° group	Not sign. (p = .0782)	Not sign.	.85
Brake initiation time relative to glance dwell			
12° group / 40° group	Not sign. (p = .1086)	Not sign.	.83
12° group / 60° group	Sign. (p = .0088)	Sign.	1.9
40° group / 60° group	Sign. (p = .0099)	Marginally sign.*	1.9

* Marginally significant here means that the 95 % HPD is not overlapping zero, but it does overlap the ROPE.

through the tested eccentricities

3.2.3. The brake response process

When the redirection of glance from off-road to on-road is complete, the next step in the driver's response process is to react to the oncoming threat by initiating an avoidance maneuver, either by braking or by steering. In Fig. 8 the initiation of the avoidance response is marked by a purple (braking) or yellow (steering) diamond. Only one out of the 52 drivers (1.9 %) tried to steer out of the situation. However, the steering was closely followed by pressing the brake pedal (within 0.25 s).

Fig. 14 shows the distribution of brake initiation times measured from the start of the glance transition (left) and from the start of glance dwell (right) respectively. The figure includes all 52 test participants, including those who did not look back towards the road. All drivers that did not initiate avoidance braking before colliding are visible in the upper (red) part of the diagrams.

From Fig. 14, it is clear that only a low number of test participants perform avoidance braking in the group looking away from the road with the highest eccentricity (60°). Only 20 % of the drivers have time to initiate a brake response in this group, while the corresponding numbers for the 12° and 40° groups are 50 % and 64 %, respectively. The trend is similar when studying only those participants who had time to start a glance transition before the end of the secondary task, with 50 % of those in the 60° group performing an avoidance brake maneuver compared to 75 % and 82 % respectively in the 12° and 40° groups.

Moreover, Fig. 14 shows that the time between glance and brake response is increasing with increasing eccentricity. The mean time to brake initiation from glance transition start increases with 0.16 s and 0.17 s as the corresponding eccentricity for the groups increases with 28° (between 12° and 40°) and 20° (between 42° and 60°), respectively. The corresponding mean increase in time to brake initiation from glance dwell is 0.09 s and 0.2 s. The statistical significance of this trend was analyzed using both a frequentist approach and Bayesian approach (with a ROPE of +/- 100 ms), see Table 1. Figures illustrating the posterior distributions for the Bayesian analysis are provided in Appendix C. The between-group difference was significant when comparing the 12° group and the 60° group, measuring from glance transition start. Moreover, it was marginally significant (i.e., the HPD did not overlap zero but it did overlap the ROPE) when comparing the 12° group and the 40° group. When measuring from glance dwell start, the differences were still significant between the 12° group and 60° group and marginally significant between the 40° group and 60° group. The effect sizes, in terms of Cohen's d (Cohen, 1988), are also presented in Table 1. There was a large effect size (d > 0.8) for all conditions, except for the 12° and 40° groups when measuring the brake initiation time relative to glance transition, where the effect size was smaller but still showed an effect (d = 0.39).

4. Discussion

Contrary to what could be expected from literature, indicating a delayed response time for higher levels of eccentricity (Berg et al., 2007; Burns et al., 2000; Lamble et al., 1999; Wittmann et al., 2006), the current experiment found that the time to glance redirection from the start of lead vehicle deceleration was independent of eccentricity. The expected effect of eccentricity was observed only when studying the time to brake initiation from the start of glance redirection. This glance-redirection-to-brake-initiation time was significantly higher for larger eccentricities than for small eccentricities. In addition, but as expected, more drivers missed responding to the threat (glance redirection and corresponding brake or steering response) at a high eccentricity.

4.1. Glance response times are unaffected by eccentricity angle

The glance response times for the participants in the experiment described in this paper are similar for all studied eccentricity levels. Though many studies show an increased response time with increasing eccentricity for various tasks, the literature is inconclusive regarding in which conditions this is really the case (for an overview see Kwon, 2010). The results from the current experiment indicates that the glance response time is not influenced by the gaze eccentricity, *as long as the driver actually looks back* towards the road. However, there seems to be a higher tendency to not look back at all for high eccentricities (60°), while this is not true for moderate eccentricity levels (up to, at least, 40°). These results indicate that the driver response is indeed influenced by the eccentricity of the gaze, but that this effect (1) mainly influences the probability of detecting the threat at all, rather than delaying all responses, and (2) is only present at high eccentricity levels (> 40°). One reason for a poorer detection probability in the far periphery could be different visual field capabilities among the drivers. The requirement of visual field for European drivers is 120° (European Union, 2006), corresponding to 60° in each direction. That is, the secondary task in this experiment is positioned just on the limit of the requirements for the high eccentricity group. This could explain that some drivers were not able to detect the threat using their peripheral vision, while those drivers that did detect the threat had the same average glance response time as the drivers in the low and moderate eccentricity groups. Note that we did not measure the participants' functional field of view, which may be a way to support or refute the impact of different effective field of view across drivers on the study results.

The glance response times, for the drivers who had time to look back in the 60° group, showed a higher variability than the responses in the 12° and 40° groups. In particular, most drivers had either a quick or a slow response, with very few responses around the mean response time. One reason for this could be the limited number of test participants. Only eight drivers had a measurable glance response time in the 60° group, compared to 12 and 11 in the other two groups respectively. Another explanation could be that the glance redirection for the drivers with a relatively short glance response time, i.e. below 2.2 s, may have been initiated due to some other factor than the forward threat and should have been excluded from the analysis similarly to the test participants corresponding to the "too early glance back on-road"-human performance deviation type. Thus, these drivers presumably looked up due to other factors than the detection of a forward threat, and it took some time while looking on-road to collect evidence for braking. This is in contrast to the other test participants who likely collected most of the evidence for braking while still looking off-road.

The severity of the brake event in the experiment described in this paper was high, and the lead vehicle brake unexpected to the test participants. As a consequence, the drivers had very limited time to react to the threat before the collision and the reactions occurred late in the event sequence. Actually, many drivers did not have time to react at all. That is, the drivers did not initiate a glance transition before the secondary task naturally allowed the drivers to look back to the road (at approximately three seconds), just before the crash. At the highest eccentricity (60°), the majority of the drivers failed to start the glance transition within this time frame. In previous similar studies, the main aim has generally been to study response times in relation to increasing eccentricity (Berg et al., 2007; Summala et al., 1998; Wittmann et al., 2006), but few publications have studied the number of response failures depending on eccentricity. In one such study, however, brake reaction time to visual stimuli was studied: Burns et al. (2000) report, in line with the results in the current study, a significantly higher number of missed target detection for high, compared to low, vertical eccentricity, with less of a difference for horizontal eccentricities.

4.2. Delayed brake response times (from glance back) for increasing eccentricity angles

Proceeding to the analysis of the motor response time of the drivers, both brake and steer responses were observed among the test participants. However, avoidance steering was only initiated by one single driver and it was closely followed by a brake response (0.25 s). Since the motor delay corresponding to moving the foot from the throttle to the brake pedal usually is around 0.15−0.3 s (Davies and Watts, 1969; Snyder, 1976), the decision to brake was more or less simultaneous to the decision to steer. Thus, the brake initiation time for this test participant can be analyzed in the same manner as the brake initiation times for the rest of the participants.

Concerning brake response time, there is a much clearer influence by the eccentricity of the secondary task, than was observed for glances: Increasing eccentricity seems to delay the brake response time when measured both from the initiation of glance transition and the dwell of the gaze on-road. The results showed some significance both using frequentist and Bayesian analysis methods, under the assumption that the responses are normally distributed. The level of significance differed somewhat depending on if the brake response times were measured from start of glance transition or start of glance dwell, with the difference being smaller between the 12° and 40° group and larger between the 40° and 60° group for the latter. This difference arises from non-equal mean glance transition times between the groups, with the longer transition times for high eccentricity groups likely due to these transitions being a sequence of several saccades.

The delayed braking response at high eccentricities was expected since it is in line with results from previous similar studies (Berg et al., 2007; Lamble et al., 1999; Wittmann et al., 2006). While the studies by Wittmann et al. (2006) and Berg et al. (2007) both report a significant effect on brake reaction time with increasing eccentricity, both studies focus on the response to a light source. However, Lamble et al. (1999) studied the brake response time to a decelerating lead vehicle and observed that drivers braked at a lower time-to-collision, defined as the time until a lead vehicle collision would occur if the following vehicle's driver would continue at constant speed, when performing a secondary task at higher eccentricities. The drivers in the study were, in contrast to the drivers in the study described in this paper, subject to a forced peripheral vision paradigm, where they were instructed to concentrate their gaze on the secondary task and brake as soon as they detected that the lead vehicle was approaching. The scenario was also much less severe than the scenario described in this paper, with the lead vehicle braking with 0.87 m/s^2 (less than 10 % of the deceleration in this study) at a speed of 50 km/h. The results in this paper supports that the brake response is dependent on looming and extends the conclusions to be valid also in very critical and unexpected scenarios.

The increased brake response times for higher eccentricities in combination with the unaffected glance response times indicate that the drivers collect evidence for braking using their peripheral view during off-road glances, but that the same information may not be used to redirect the gaze towards the road in front. That means, the collected evidence mainly serves as a way to dictate the brake initiation time, not to redirect the glance towards the road. However, since the braking is delayed to a higher extent for high eccentricities, compared to low eccentricities, the amount of evidence for braking accumulated during the glance seems to decrease with increasing eccentricity. Several publications suggest that looming level has an essential effect on the driver's brake response time (Fajen, 2005; Kiefer et al., 2005; Kondoh, 2014; Lee, 1976; Markkula et al., 2016) and there are also studies which indicate that the perception of looming does not decrease in the periphery of the visual field (Li and Laurent, 2001; Stoffregen and Riccio, 1990). If drivers' reactions only depend on the current looming level, and the perception of looming is independent of eccentricity, no delayed brake response times would be observed for high eccentricity angles. However, recent models of driver brake initiation argue for the brake initiation being dependent on the amount of unexpected *accumulated* looming, the looming prediction error (Bianchi Piccinini et al., 2019; Markkula, 2014; Svärd et al., 2017). The delayed brake response times could then be interpreted as being due to the lower rate of looming accumulation for higher eccentricities, rather than the looming cue in itself being weaker. The driver detects the same amount of looming when looking on-road as when looking off-road, but the accumulation during off-road glances is going on at a slower rate since it is cortically processed by the driver's peripheral vision. In the periphery of the visual field, there is a decrease in the density of retinal receptors as the distance from the fovea increases; and in the visual centre in the brain there is a lower proportion of cortical processing (Findlay and Gilchrist, 2003). This leads to a limited perceptual performance at higher eccentricities, when compared to the central parts of the visual field. Although humans are better at detecting motion in the periphery, looming is a combination of *both* motion and acuity-dependent perception, which may contribute to a slower accumulation rate at high visual eccentricities. A slower looming accumulation rate would imply that the total collected evidence for braking is lower for higher eccentricities at the time of looking back, which demands more evidence to be collected (i.e., longer time) during the subsequent on-road dwell, before the decision to press the brake pedal is made. The glance response time could possibly depend on the absolute level of looming, rather than the accumulation, since the detection of that level would be independent of eccentricity. There is also a possibility that the glance response time is not dependent on looming at all, but the glance redirection could be initiated by other cues such as the detection of motion.

4.3. High eccentricity angles are associated with an increased proportion of human performance deviations

Out of the 83 test participants in the current experiment, 37 % exhibited a glance or driving behavior that was not explicitly intended (i.e., not the dominant behavior) in the experimental design. These were referred to as human performance deviations and were classified into different categories depending on their consequences for the subsequent analysis. The first category, human performance deviations resulting in data loss, could be regarded as driver or operator errors in relation to the a priori given instructions, classified as operator mistakes or driver non-compliance situational errors, using the classification by Reason (1990). This category was not interesting for the further study of driver responses due to the resulting variability in situation kinematics or a lack of off-road glance pattern. Though the second category, human performance deviations resulting in several or very early on-road glances, could be seen as a human performance deviation from the perspective of fulfilling the secondary task and classified as a lapse according to Reason's (1990) error classification system. This human variability in glance pattern is an interesting part in the driver's overall response process. It was observed that, in particular, check glances and "what was that"-glances were a lot more frequent for test participants in the higher eccentricity groups (40° and 60°). A reason for this could be that the secondary task required the participants to look away for three seconds (if not check glancing), which is a very rarely occurring natural glance duration (e.g., less than 1.4 % of the 1196 off-road glances in normal driving car-following data, presented in the work by Bärgman et al. (2015), were longer than three seconds – data from the SHRP2 naturalistic driving study, Transportation Research Board of the National Academy of Sciences, 2013). The rare occurrence of long off-road glances was also observed in the statistical analysis forming the basis for a visual time sharing (VTS) reference model, presented by Morando et al. (2019b). Only 4 % of the glances in the empirical data used to build the VTS model were longer than two seconds (Morando et al., 2019c). The average glance duration may however be prolonged, and the off-road glance distribution shifted towards longer glances, when introducing a secondary task (e.g., see the visual sampling model by Wierwille, 1993). For example, the radio tuning task has been studied by Rockwell (1988) where the mean glance duration was above one second, with only around 18 % of the off-road glances longer than two seconds, but none longer than three seconds. The glance distributions related to more modern radio tuning were found to be similar in a study by Lee et al. (2018) based on data from the second Strategic Highway Research Program (Transportation Research Board of the National Academy of Sciences, 2013).

When performing a secondary task at a low eccentricity (12°), the drivers may feel that they have a better appreciation of the forward road in their peripheral field of vision, than what they have at 40° or 60°. At higher eccentricities, the drivers are thus more prone to check glances as a way to reduce uncertainty about what is going on in front of the vehicle (e.g., see Senders et al., 1967; Victor et al., 2014). This is discussed in terms of precision and tied to the predictive processing framework by Engström et al. (2018). The more and the longer the drivers look away, the more uncertain their prediction of the future state of the traffic situation ahead (i.e., the lower the precision of the predictions). This will encourage the driver to perform actions to increase the precision (minimize uncertainty) through, for example, visual scanning. The frequent check glances for high eccentricities in our experiment can also be compared with the results by Stoffregen and Riccio (1990), where the dodging movements to an oncoming ball were started at higher time to contact for higher levels of eccentricity. Instead of dodging a ball with some marginal due to uncertainties in physical properties, location, and similar, the drivers seek to enhance their knowledge about the lead vehicle behavior by glancing on-road earlier than they would have done if performing a secondary task at a low eccentricity, where more information about the forward roadway is better available in the peripheral view.

Since the amount of performance deviations increase with increasing eccentricity angle, it could be hypothesized that the drivers would also vary their speeds to a higher degree when looking away at large angles. In this study, a small increase in initial speed variation was observed, as well as a small effect of decreased average speed at higher eccentricities. This was likely due to that the brake event was initiated in the second game round of the secondary task, that is, the drivers seem to have more difficulty in keeping speed when looking off-road with higher eccentricities, and that drivers tend to be a little bit more careful when looking further away from the forward roadway. Several previous studies have shown that the mean speed decreases, in some cases in combination with a speed variability increase, when the driver is engaged in a secondary task (Choudhary and Velaga, 2017; Rakauskas et al., 2004; Young and Regan, 2007). The reason for that could be a compensatory behavior by the driver to maintain an adequate level of safety in case of unexpected events (Choudhary and Velaga, 2017), similar to what is done by drivers with visual field defects (Coeckelbergh et al., 2002). It seems reasonable that the compensatory behavior should be more pronounced when the secondary task is performed at higher eccentricities, as seems to be the case in this experiment, but this is an area that seems to be sparsely explored in the literature. Moreover, the increased speed variability for higher eccentricities could be compared to the observed degradation in lane keeping observed by Summala et al. (1996), indicating that the driver at higher eccentricities do not have all the necessary spatial information to accurately control speed and lane position.

4.4. Future work

The results from the current experiment indicates that the drivers collect evidence for braking while looking off-road. This could be used to extend existing driver models designed for lead vehicle scenarios to account for off-road glances of different eccentricities, which would increase the representativeness of simulation results if the models are used for virtual analysis of road safety benefit. For example, the quantitative model for brake onset and control in lead vehicle scenarios described by Svärd et al. (2017) could be extended by introducing a parameter $\eta(\alpha)$, determining the rate of looming accumulation, according to Eq. (4).

$$A(t) = \int (\eta(\alpha)K\,\varepsilon(t) - M + v(t))\,dt \tag{4}$$

where $A(t)$ is the total accumulated evidence for braking, α denotes the eccentricity angle, $\varepsilon(t)$ is the looming prediction error, K and M are free model parameters and $v(t)$ is Gaussian zero-mean white noise. When the accumulated evidence for braking, $A(t)$, reaches a certain threshold A_t, a brake adjustment is issued.

To reduce the problem with participants who don't have time to look back on-road or initiate braking, and to make the results more comparable with previous literature, the brake response time could be further studied in a forced peripheral vision setting similar to what was done by Lamble et al. (1999). The drivers would then be told that the lead vehicle is going to brake, and instructed to focus their gaze on the secondary task at all times, while told to brake as soon as judged necessary. The results would give more detailed information about the drivers' brake response processes and how it is influenced by the eccentricity. This would also eliminate the risk that drivers looks up towards the forward roadway because of other reasons than an upcoming threat, for example due to a desire to control the vehicle laterally.

Assuming the driver reacts as a response to the forward threat, a comparative study to distinguish between glance responses due to peripheral looming and glance responses due to peripheral movement can be a next step to understand the mechanisms behind the glance response. Even if the driver uses looming level as the major cue for glance redirection, the variations in speed and looming profile among the participants in this experiment makes it difficult to draw conclusions about the exact looming threshold for different degrees of eccentricity. In addition, the number of test participants who redirect their gaze is fairly low, in particular in the 60° group. Having a higher number of participants who look back on-road because of the forward threat, as well as a higher number of participants who perform avoidance braking, would give more strength to the results.

4.5. Limitations

The current study was performed in a simulator environment, which could influence the response process of the driver in several ways. First of all, although the simulator being a high fidelity moving base simulator mainly used for simulation of vehicle dynamics, there are limitations in how realistic the driving feels. The vehicle response to speed changes and steering input may differ from an authentic car driving on a real road. Also, the visual cues may be influenced by the graphics of the simulator. Contrasts and colors may be experienced in a somewhat different way compared to when driving in a real outside environment. Being part of a controlled study, the participants may also have a certain level of expectancy in that something out of the ordinary will happen, even though the true aim of the study was not revealed in beforehand.

The results in this paper is based on driver response times, but the visual cues used by the drivers as a basis to their reactions are not completely clear. In literature, the looming cue is widely used to determine brake response times, but the results from this study do not reveal whether the glance responses are due to peripheral looming or movement detection, or the need of lateral control. Lateral control of the vehicle has been out of the scope for this study, but glance behavior induced by the needs of lateral control could influence the interpretation of the study results.

Finally, it is important to note that this experiment only takes horizontal eccentricity and longitudinal motion into account. The conclusions may not hold for corresponding vertical eccentricities. Previous studies (Lamble et al., 1999; Wittmann et al., 2006) have shown that the influence of eccentricity is different in the horizontal and vertical direction, supposedly due to that the eye is not spherical but asymmetric in these planes. Lamble et al. (1999) found that the thresholds for detecting a decelerating lead vehicle were higher in the vertical than in the horizontal plane. Wittmann et al. (2006) confirmed the higher detrimental effect of vertical eccentricity compared to horizontal for the task of reacting to an eccentric light by pressing the brake pedal while at the same time performing a lane keeping task. Since the secondary tasks in the current experiment were positioned just below the dashboard level, the drivers are likely to experience effects from both vertical and horizontal looming. Though, the horizontal angle should have the major influence on the results because of its larger size.

5. Conclusions

This paper describes the results from a between-group simulator experiment, where drivers were subject to an unexpected severe braking of a lead vehicle, while performing a visual-manual secondary task positioned at different degrees of eccentricity. The drivers' response processes in terms of glance response time and brake initiation were studied to identify factors important to model driver response to perceptual input during off-road glances. Contrary to expectations, it was found that, for the drivers that looked back to the road at all during the critical event, the eccentricity of the secondary task did not have an effect on the time to redirect glances from the secondary task location to the forward road after the lead-vehicle-deceleration began. However, the eccentricity influenced the overall tendency to look back towards the road, with fewer drivers reacting to the forward threat at a high eccentricity (60°) than at low eccentricities (12° and 40°).

The expected effect of delayed response times for higher eccentricities of the secondary task was observed only for the brake response process. The brake initiation time, measured from start of glance transition or glance dwell on-road, increased with increasing gaze eccentricity. Similar to what was observed for glance responses, the proportion of drivers reacting to the forward threat, by performing avoidance braking, was low at a high eccentricity (60°).

Human performance deviations limited the number of observations for the analysis of the driver's response processes. That is, drivers proved to be more prone to performing check glances back to the road when looking away at high eccentricity angles, while long off-road glances at lower eccentricities were easier accepted by the drivers. This was likely the effect of a desire to minimize uncertainty of what was happening on the road in front by visual scanning.

It can be concluded that drivers seem to collect some evidence for braking during off-road glances using peripheral vision, but that the mechanism that guides the drivers gaze back towards the road is separate from that initiating the avoidance braking maneuver. The amount of accumulated evidence for braking is lower at high eccentricities and seems to be used to evaluate the need for avoidance braking only, after the, eccentricity independent, gaze redirection. This knowledge will be used for the implementation of extensions of existing driver brake response models, to permit these to also account for off-road glance behavior.

Declaration of Competing Interest

Malin Svärd and Trent Victor were, at the time this study was conducted, employed by Volvo Car Corporation, located in Gothenburg, Sweden. This study may impact how Volvo Car Corporation choose to develop their products.

CRediT authorship contribution statement

Malin Svärd: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization, Project administration. **Jonas Bärgman:** Methodology, Writing - review & editing, Supervision. **Trent Victor:** Methodology, Writing - review & editing, Supervision.

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Appendix A. – Secondary task game sequence

Table A1
Description of the secondary task game sequence and corresponding driver actions.

	Game action	Driver action
1	If first game round: Alerting sound	Identification of on which screen the game is presented
2	Display: "Press the screen"	Possibility to look on-road
3	Wait for driver input	Screen press
4	Countdown ("3", "2", "1")	Possibility to look on-road
5	Disc starts moving	Disc tracking
6	Disc changes shape to diamond and back again (while still moving)	Disc tracking
7	Disc stops moving and disappears	Possibility to look on-road
8	Display: "In which area did the circle change shape?"	Possibility to look on-road
9	Wait for driver input	Screen press
10	Display: "Correct" or "Wrong"	Possibility to look on-road
11	If last game round: "Game over. Total score: XX", else starting over at "Press the screen"	Possibility to look on-road

Table A1 describes the sequence of the self-paced game, used as secondary task in the simulator experiment.

Appendix B. – Bayesian analysis method

Below, a simplified version of the Bayesian analysis method described by Morando et al. (2019b) is described. This is used to analyze the statistical significance of the results in Section 3.2.3.

First, a general linear model was defined with a likelihood function according to equation (B-1).

$$y \sim \mathcal{N}(X\beta, \sigma) \tag{B-1}$$

where y is the vector of response times, X is the vector of predictor variables corresponding to different eccentricity levels and β denotes the fixed effect parameter vector. A vague prior normal distribution of the parameters was defined as in equation (B-2) and the standard deviation distribution as in equation (B-3).

$$\beta \sim \mathcal{N}(0, 2) \tag{B-2}$$

$$\sigma \sim half\mathcal{N}(3) \tag{B-3}$$

Python (version 3.7.4) and the probabilistic programming library PyMC3 (version 3.7) was used to analyze the experimental data (Salvatier et al., 2016). 6500 samples were drawn from the posterior distribution using the No-U-Turn Sampler (NUTS) and two Markov Chain Monte Carlo (MCMC) chains (Hoffman and Gelman, 2014). Out of these samples, 500 in each chain were discarded as burn-in to let the Markov chain stabilize at its stationary distribution. This sampling resulted in a joint posterior distribution that could be summarized by the Highest Posterior Density (HPD) interval. The HPD can be considered a summary of the certainty of the measurement points, similar to the confidence interval in a frequentist analysis. The group comparison was conducted through an analysis of how a Region Of Practical Equivalence (ROPE) overlaps with the HPD, (e.g., see Martin, 2018). The ROPE is a range of values that can be considered equivalent for practical purposes (Kruschke, 2018) and was here á priori set to +/- 100 ms (for this type of analysis – decided in workshop with experts not having seen the study results before the decision of ROPE). Consequently, if a range of values +/- 100 ms around zero did not overlap with the 95 % HPD, the distribution of response times for the groups were considered significantly different.

Appendix C. – Posterior distributions from the Bayesian analysis

Figs. C1–C4 show the posterior distributions from the Bayesian analysis in Section 3.2.3. The region of practical equivalence (ROPE) is depicted with a horizontal green line and the Highest Posterior Density (HPD) with a horizontal black line.

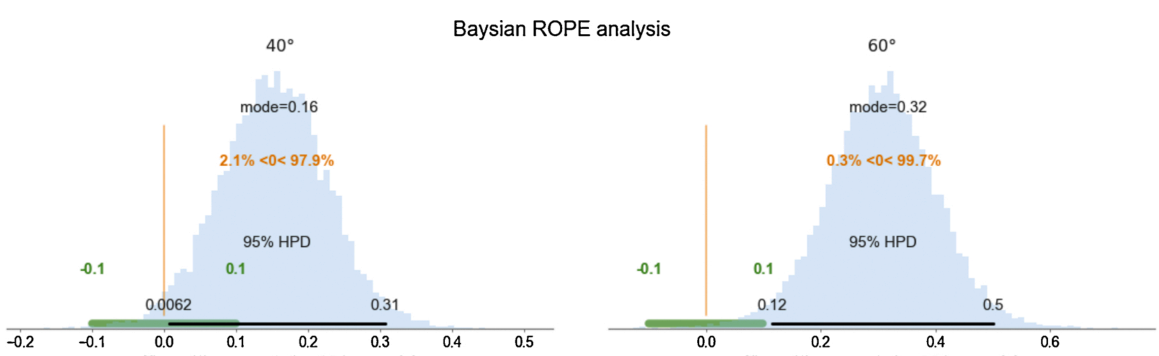

Fig. C1. Bayesian ROPE analysis of brake initiation time relative to start of glance transition, 12° vs. 40° (left) and 12° vs. 60° (right).

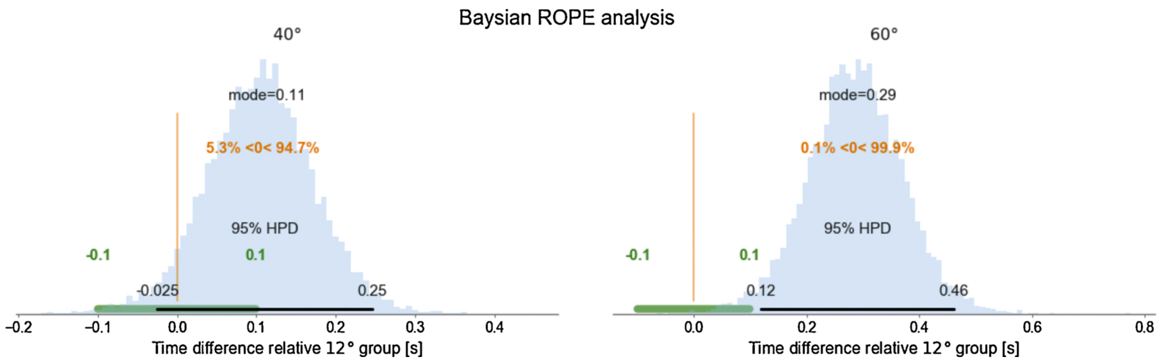

Fig. C2. Bayesian ROPE analysis of brake initiation time relative to start of glance dwell, 12° vs. 40° (left) and 12° vs. 60° (right).

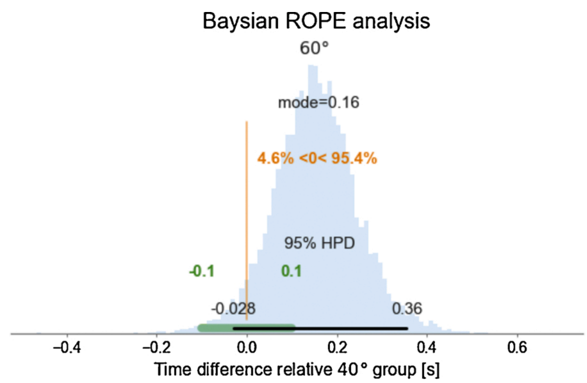

Fig. C3. Bayesian ROPE analysis of brake initiation time relative to start of glance transition, 40° vs. 60°.

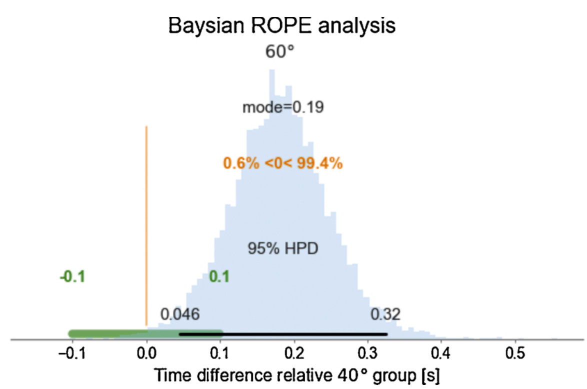

Fig. C4. Bayesian ROPE analysis of brake initiation time relative to start of glance dwell, 40° vs. 60°.

Appendix D. – Data inclusion sensitivity

When studying the glance response process, it was decided to exclude test participants performing check glances from the analysis. The reason for this was to reduce the risk of having responses that were not directly due to the detection of a forward threat, but rather reflected other factors. The choice of a driver subset relevant for the detailed response process analysis may influence the results to a larger or lesser extent depending on which performance deviations that are judged acceptable. Fig. D1 and D2 show the glance and brake response times respectively when, in addition to the 52 test participants analyzed in Section 3.2, all test participants performing "too early glances" are included. The total number of test participants is 57 (21 in the 12° group, 15 in the 40° group and 21 in the 60° group). The overall conclusions from the analysis of the smaller dataset with 52 test participants, presented in Section 3.2, still hold, but with a somewhat lower significance (p) for the brake initiation time results. In the figures, the participants with too early braking are marked with red dots since these are related to a human performance deviation.

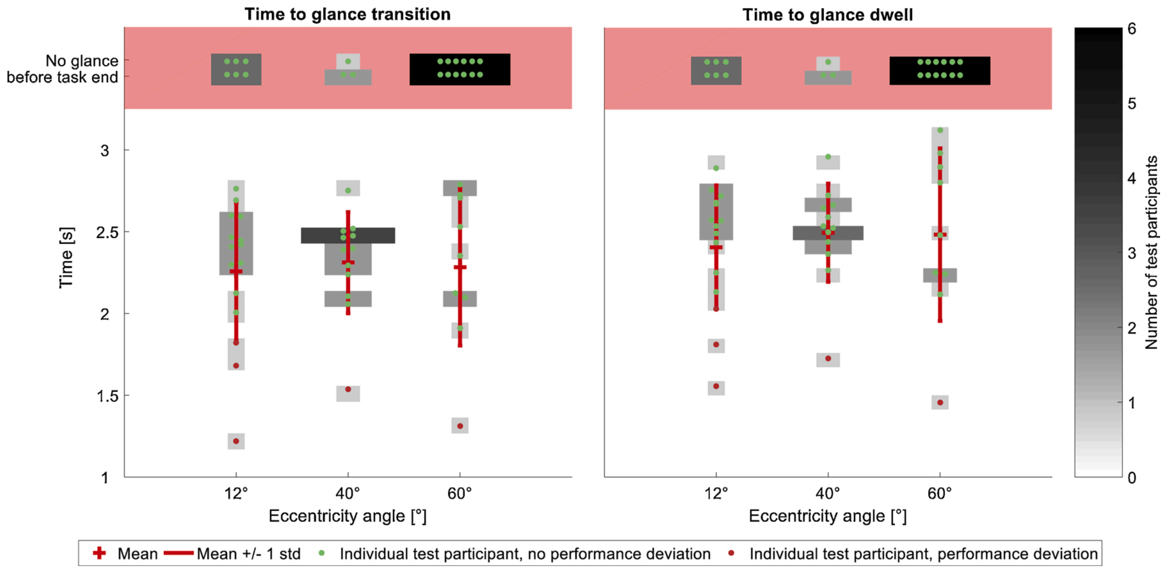

Fig. D1. Glance response times for all groups when including participants with too early braking. The widths of the horizontal bars correspond to the number of test participants ending up in that bar, relative to the total number of test participants in the group, while the color of the horizontal bars reports the number of test participants in that bar, independent of group. The dots represent individual data points (i.e., the response times for individual drivers). *Left:* Time from lead vehicle deceleration start to start of glance transition. *Right:* Time from lead vehicle deceleration start to start of glance dwell.

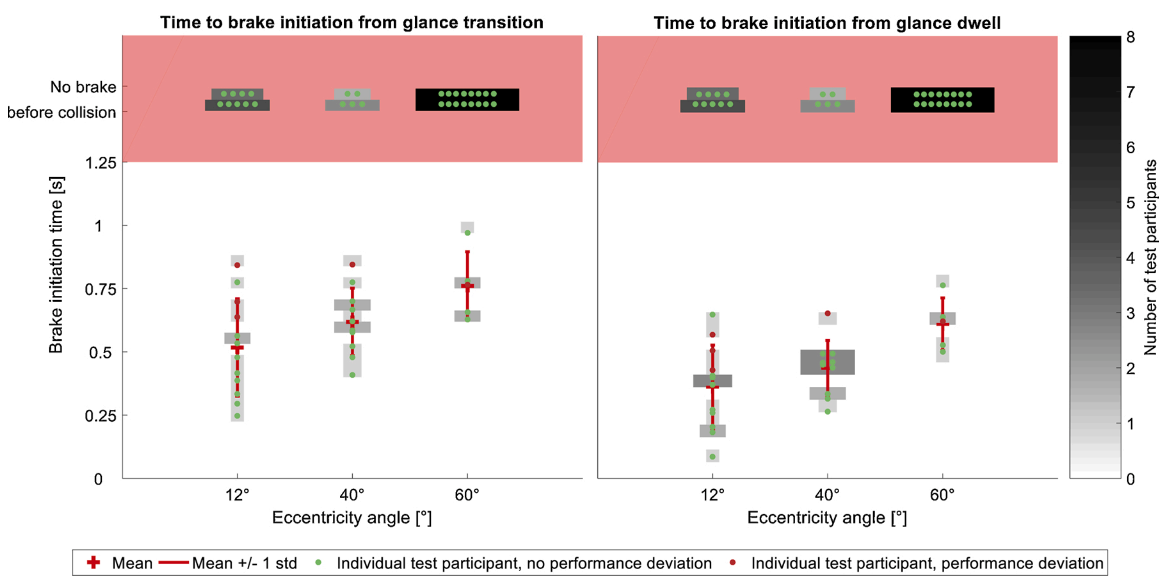

Fig. D2. Brake response times for all groups when including participants with "too early glances". The widths of the horizontal bars correspond to the number of test participants ending up in that bar, relative to the total number of test participants in the group, while the color of the horizontal bars reports the number of test participants in that bar, independent of group. The dots represent individual data points (i.e., the response times for individual drivers). *Left:* Time from start of glance transition to brake initiation. *Right:* Time from start of glance dwell to brake initiation.

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